COUPLED MICROSCOPIC MODELLING OF TRAFFIC DEMAND AND TRAFFIC FLOW ON A CITY LEVEL

Daniel Krajzewicz
Institute of Transport Research, German Aerospace Center
Rita Cyganski
Institute of Transport Research, German Aerospace Center
Matthias Heinrichs
Institute of Transport Research, German Aerospace Center
Jakob Erdmann
Institute of Transportation Systems, German Aerospace Center

1. INTRODUCTION

Microscopic models of traffic demand and traffic flow have reached a maturity which allows their usage for investigating large-scale effects of measures and/or developments. In microscopic models, every participant is described individually by a set of attributes. Demand models use attributes such as the age, employment state, sex, home location, and the availability of mobility options for computing the person's mobility in a region defined by activity locations and mode-dependent travel times. Traffic flow models replicate the progress of individual users – may they be vehicles or individual persons as well – through a given transportation network. As in demand models, every participant is defined using a set of attributes, mainly ones that describe its physical attributes, such as the maximum acceleration/deceleration capabilities, the maximum speed or the emission class.

The microscopic representation of user and vehicle groups is intrinsically sensitive to a large number of influences, because the used parameters directly determine the individuals' behavior. The usage of disaggregated populations and vehicle fleets additionally enables to investigate the effects of measures that influence only a part of the population or the vehicle fleet, such as environmental zones or parking fees.

At first, the benefits of using microscopic models are outlined. Then, the fundamentals of microscopic models for traffic flow simulation and demand modelling are given respectively, using the microscopic traffic flow simulation "SUMO" (Krajzewicz et al., 2012) and the agent-based demand model "TAPAS" (Heinrichs et al., 2016; Hertkorn, 2005) as examples. Afterwards, an example use cases that demonstrates why it is necessary to employ both simulation types is given. Then, a new system that couples both simulations for diminishing the missing interaction between traffic performance and mode choice is outlined. The report ends with a summary.

2. WHY MICROSCOPIC?

Microscopic approaches replicate the behavior of a system by modeling the system's individual participants. Macroscopic approaches, in contrary, replicate the system's dynamics without regarding the individuals the system consists of. Thereby, macroscopic traffic flow simulations model the behavior of the traffic flow by computing its attributes – flow, speed, and occupancy – directly, usually based on models of gas or fluid dynamics. Microscopic traffic flow simulations compute how the individual vehicles traffic flow consists of move through the road network. Similarly, microscopic demand models resemble the population's mobility behavior by computing each individual's personal choices for choosing a location to travel to, the transport mode to use, and the time at which the trip shall take place. The traffic demand at a given time is thus generated as the sum on individual decisions on movements. Macroscopic traffic demand models use aggregated populations and divide them on available destinations, following the region's found or assumed modal split.

Microscopic simulations of both, the demand as well as traffic flow hold several advantages when compared to macroscopic ones. The major is of course the higher, disaggregated resolution in time and space. This disaggregated view at the individuals additionally allows modifying and accordingly investigating actions that affect sub-groups of the overall population and vehicles or even the respective individuals only. This counts for the respective simulation's input, processing, and outputs.

As for the inputs, e.g., the demand model's household attributes can be used to assign vehicles of a certain type to them. Doing so not only increases the quality of a vehicle fleet's spatial distribution, but and allows for more exact modeling of a new technology's diffusion, matching the socio-demographic attributes of the population. Accordingly, a non-homogeneous vehicle fleet can be easier modeled using microscopic traffic flow simulations whereas a macroscopic view uses an averaged view at the fleet and the distinction between different vehicle types is lost.

During the processing, microscopic models can distinguish between specific types of persons or vehicles. For persons, the availability of certain mobility options, such as car- or bike sharing accounts, can be modeled. For vehicles, it allows for modeling specific vehicle behavior based on new technologies, such as vehicular communication or autonomous driving.

Microscopic simulations usually generate outputs that describe each person's or vehicle's progress. It is thereby possible to regard each sub-group or individual explicitly. Embedded models of pollutant or noise emissions increase the amount of possible measurements that can be obtained from a traffic flow simulation.

Summarizing, microscopic approaches for traffic flow and demand modelling offer the following benefits when compared to the respective macroscopic ones:

- Traffic flow:
  - High, disaggregated time resolution;
  - Highly detailed road network with turn restrictions, lane assignments, etc.;
  - explicit definition of infrastructure units, such as variable speed signs or traffic lights with the replication of their respective real-world timings etc.;
  - Retrieval of fine-grained vehicle and/or person trajectories that may be aggregated for obtaining global measures or can be evaluated individually;

  - Replication of new technologies, such as assistance systems or electric vehicles for the complete or only sub-set of the vehicle fleet;
  - Replication of systems which affect or use only a subset of vehicles on roads.
- Demand model
  - High spatial resolution by allocating persons and activity locations at their geo-coordinates;
  - High, disaggregated time resolution;
  - Assignment of individual mobility options;
  - Replication of demographic, socio-demographic and financial changes affecting the complete or a sub-parts of the population;
  - Evaluation of changes in allocation and capacities of activity locations;
  - Replication of the influences of regulative, organizational changes.

Demand and traffic flow simulations are described and discussed in more detail in the following sections, mainly based on the experiences gained during the development and application of the tools “TAPAS” and “SUMO”.

3. MICROSCOPIC TRAFFIC FLOW SIMULATIONS

Microscopic traffic flow simulations are known since the 1950’ies and grew increasingly popular in the last decades (Pipes, 1953). In the following, the major tasks a microscopic traffic flow simulation should perform are outlined. Then, the models a microscopic traffic flow simulation consists of are presented, followed by a description of the needed input data. Afterwards, a summary of the applications of such simulations, and finally the shortcomings of microscopic simulations are given.

3.1 Major Tasks

The purpose of microscopic traffic flow simulations is to replicate the behavior of individual participants through a road network. Because every road traffic participant is individually modeled, microscopic traffic flow simulations are capable to replicate different vehicle types. Usually, the distinction between passenger vehicles and heavy duty vehicles is made. More recent applications resemble the statistical distribution of vehicle emission types, promising a higher quality of the overall emission computation.

Traffic flow simulations must resemble the overall characteristics of traffic flow, such as capacity breakdowns, as well as the individual vehicles’ behavior in dependence of the environment, mainly traffic lights. While microscopic traffic flow simulations allow to track every single vehicle’s progress through the road network, including all vehicle maneuvers such as car following, turnings and accelerations as well as the overall trajectory, often aggregated measures that either describe a vehicle’s complete drive or the situation at the network’s roads are used.

3.2 Models

The major application for microscopic traffic flow simulations is to replicate the behavior of single vehicles the motorized individual traffic consists of. Usually, a distinction is done between the longitudinal behavior – choosing the speed – and the lateral behavior – changing the lane. A common approach to model the speed a vehicle uses is the car-following paradigm, where a driver is assumed to follow a vehicle in front. The major idea behind this approach is that usually, driving is done in a manner where collisions do not occur. Thereby, the following rule that describes the safe-gap paradigm holds:

$$d(v_{Leader}) + g \geq d(v_{Follower}) + v_{Follower}\tau \qquad (1)$$

Where $d(v)$ is the breaking distance, given the velocity v, $v_{Follower}$ is the velocity of the regarded vehicle, and v_{Leader} the velocity of the vehicle in front of it, τ is the driver's reaction time, and g is the gap between both vehicles. This formula describes the situation where a following vehicle is still capable to brake if the leading vehicle brakes, regarding the speed of both, their distance, and the driver's reaction time.

Different models for a collision free car-following behavior exist, where the most prominent are the IDM (Treiber et al., 2000), the Krauß model (Krauß et al., 1997), or the model developed by Kerner (Kerner et al., 2008) for replicating the three-phase theory of traffic flow. A comparison and benchmarking of several car-following models can be found in Brockfeld and Wagner, 2004, and Brockfeld et al., 2005.

Lane-changing is more complex, because aspects, such as using the correct lane to progress through a road network where each lane allows a set of possible directions, the interaction with other vehicles including opening a space for letting one into a lane, latencies in changing the lane, etc. must be considered (e.g. Erdmann, 2015). Albeit being important for a proper model of the traffic flow, lane changing is less prominent in literature, maybe due to its complexity. As well, it is known that lane changing is highly interrelated to speed decisions at lower time scales, still, descriptions of such interrelations can be hardly found.

A relatively new extension to microscopic traffic flow models is the inclusion of emission models (Krajzewicz et al., 2014). Following the possibility to model a highly disaggregated vehicle fleet, these emission models cover a high proportion of nowadays vehicles by distinguishing a high variety of nowadays vehicles' emission classes.

More recently, microscopic traffic flow simulations have been extended for replicating the behavior of bicyclists and pedestrians. The latter often use a 2D-representation of the movement (Helbing and Molnár, 1995). Though, some models distinguish between the longitudinal (forward) and the lateral (lane changing) movement (Erdmann and Krajzewicz, 2015), mainly to achieve a higher simulation speed. Bicyclists behavior is relatively new in literature (Andresen et al., 2014), and currently one can hardly find models for bicyclists' lateral behavior.

3.3 Input

The data used by traffic flow simulations can be divided into two parts: the road traffic infrastructure and the traffic demand. The first is usually represented by a unidirectional graph, where the intersections form the nodes, and roads the edges. Microscopic traffic flow simulations require a very exact representation of the road network, including the correct information about the number of lanes, the connections from lanes to following roads, as well as the correct right-of-way rules, and, if given, traffic light signal schedules at intersections. Because such input data is almost never given in available digital road network representations in a sufficient quality and coverage, the according preparation of road network models for microscopic traffic flow simulations is a very time-consuming task, even if heuristics can be applied for smaller intersections.

The demand is often given in form of aggregated origin-destination matrices that describe how many vehicles travel from a traffic assignment zone to another one in a given time span. In principle, microscopic traffic flow simulations require multiple matrices to cover a day, because the traffic flow directions change between the morning and the afternoon peak. Origin-destination matrices are often given for the passenger and the heavy duty traffic separately.

More recent approaches use single individual's trips or trip chains obtained from agent-based demand models, which will be described in the next section. This approach holds several benefits. The major to name are the high spatial resolution of the input data which matches the needs of microscopic traffic flow simulation, time consistency between the trips performed by a person during the day, or the possibility to retrieve the demand for all common modes of transport.

3.4 Applications

Microscopic traffic flow simulations are used for different classes of research questions. One first to name are evaluations of new methods for real-life traffic surveillance, using e.g. cellular telephone data, Bluetooth detectors, airborne camera-based systems or similar. A second one are evaluations of new systems that attempt to improve traffic flow, such as new traffic light algorithms, schedules, or synchronizations, route guidance, or assistance systems. Here, one can distinguish between systems that change the behavior of the infrastructure, the vehicle, or both.

While the common application focusses on areas that cover only some intersections, the execution speed of current microscopic simulators allows their employment for evaluating large-scale effects, by simulation large cities at multiple real-time speeds (Krajzewicz, 2016).

3.5 Shortcomings

Especially when being applied to large-scale areas and optimization tasks, microscopic traffic flow simulations do not resemble the changes in user behavior completely. E.g., the improvement of the motorized individual traffic yields in a higher use of this mode in reality. As well, restrictions, such as speed calming, or the implementation of environmental zones, not only change the routes of individual drivers, but move a portion of those to use a different transport mode, e.g. bicycles, because the influences traffic areas are calmer and can be passed by bicycles more safely. Because microscopic traffic flow simulations use traffic demand matrices as input, and keep them static within according evaluations, these effects cannot be found in the simulations' outputs.

4. TRAFFIC DEMAND

The following sub-sections describe microscopic demand models, usually named as agent-based demand models. The order of the subsections is as for the traffic flow simulations. Again, many of the formulated statements reflect experiences gained during the development and application of the agent-based simulation model "TAPAS" at the Institute of Transport at the German Aerospace Center.

4.1 Major Tasks

Agent-based demand models describe the mobility behavior of a modeled population. This includes the computation of the destinations every simulated person wants to access, usually matching a person's daily activity plan. E.g. a worker may want to get to his work place, first, and perform a shopping or leisure activity afterwards. For this purpose, a matching activity location has to be determined. In addition, the mode of transport the regarded person uses is computed for each of the trips, taking into account that available vehicles such as cars or bikes must be returned home. The result usually consists of a trip chain along a single day for every modeled person.

4.2 Models

In TAPAS, every simulated person follows an activity plan. Such plans may be manually set up or generated from daily activity surveys as the Germany MiD (Infras and DLR, 2010; BMVI, 2009) as the case for TAPAS. These plans are assigned to single persons matching these persons' socio-demographic attributes, mainly including the person's age, sex, and employment status. As outlined, the computation of a person's movement within a modeled region that follows such an activity plan consists of two highly integrated parts for each of the activities the person aims to perform: the determination of a destination and of the used transport mode.

To select one of the possible destinations – e.g. the working place – gravity-based approaches (Hua and Porell, 1979) and Intervening Opportunities (Stouffer, 1940) are employed. The one to use can be selected within the read configuration. The first method assumes that near-by locations are chosen with a higher probability, but still regards more distant ones. The second method applies a threshold for a destination's visibility to the user.

The computation of the mode of transport to access a destination usually employs a multinomial logit model that uses the trip's attributes, such as the trip's duration or distance, the costs when being performed using the respectively evaluated mode of transport, as well as attributes which reflect the person's preferences, such as age, or sex. While many of these attributes are continuous, some categorial and binary attributes are used as well, such as the availability of a car, driving license, bike, or a public transport mode.

4.3 Input

Agent-based demand models like TAPAS need spatially fine-grained information about the population itself as well as the activities' locations and the available transportation choices. In TAPAS, each individual in the population is described by a set of socio-demographic attributes, such as his/her age, sex, employment status and by information about the mobility options available for this person, such as the availability of a public transport season ticket or a bicycle. Persons are grouped into households that hold further attributes, such as available cars or monthly income. Every household is allocated at a certain position within the modeled region, either via a geo-location or by being assigned to a dwelling (Heinrichs, 2016).

The activities' locations are allocated in space at the level of buildings or geo-locations as well. To avoid using one location only – for example the biggest and thereby mostly preferred one – locations may hold information regarding their capacity. For computing the parameters needed by the location and mode choice models, usually distance and travel time matrices are needed.

Individual transportation resources, such as cars or public transport tickets are attached to the modeled population (see also the previous subsection). Every car belongs to a certain vehicle type what allows to model and simulate different penetration rates of new technologies and using the households' socio-demographic attributes for modelling a spatially fine-grained diffusion. Additionally, global transport supply performance measures, such as travel times for all modes, are given as global matrices.

4.4 Applications

The big diversity of used inputs – disaggregated population descriptions, transportation infrastructure, as well as the locations the modeled persons may approach – allows a large variety of investigations. One common set of investigations is to evaluate how changes in available mobility options influence the behavior. This may be both, changes of existing modes, like new prices or scheduled for public transport or new travel times of motorized individual traffic, as well as the introduction of new modes, such as car-sharing.

The second major application is to predict the future traffic demand that arises from a development of the population itself. Increasingly, specific user groups are under investigation, such as tourists, impaired persons, refugees, etc. But having the locations as a further input, microscopic traffic demand models allow as well to evaluate new city concepts, such as the "city of short ways" where big malls are replaced by smaller, local shops.

4.5 Shortcomings

While being capable to determine changes in location and mode choice, sole-standing agent-based demand models fail in computing the effects on the transportation network. Distance and travel-time matrices are an input to this kind of models and are not influenced by the amount of persons that use an according part of the transportation network. In conjunction, no assignment of person routes to the road network is being performed, what e.g. disallows to compute the emission generated during each trip – despite using aggregate, coarse models that use a trip length and its mode of transport as input only.

5. EFFECTS OF DEMAND CHANGES

When looking at the shortcomings of both simulation types, one may note that both need the output generated by the respective other class as input, namely traffic demand models need travel times that may be obtained from traffic flow simulations while the latter needs the demand that is computed by demand models. As an example that demonstrates why it is necessary to evaluate both, the evaluation of the introduction of a speed limit in a city area is described in the following. Existing models of the city of Brunswick for both used simulators were used for this purpose.

In a first attempt, only the effects of the measure on traffic flow were investigated, by computing the traffic assignment for the given demand after adapting the speed limits of the influenced roads. The results are shown in Figure 1. As shown, keeping the volume, traffic omits the inner city center, crossing it only at roads for which the speed limit was not reduced. Consequently, traffic volume is increased at roads that surround the inner city center.

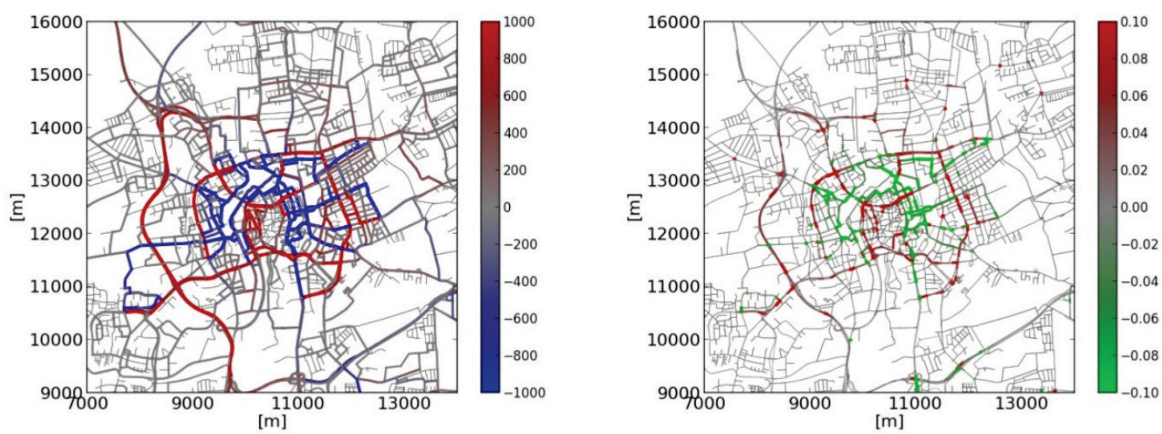

Figure 1: Changes in traffic flow in vehicles/day (left) and NO_x emissions in g/km/day (right) after introducing a tempo limit when disregarding changes in mode choice.

In a second step, the same measure was evaluated, this time incorporating a demand model. Here, the demand for the base case was computed first. Then, the travel time matrices for motorized individual traffic were adapted for determining the demand after introducing the new tempo limit. As expected, the proportion of the mode "motorized individual traffic" is lowered after introducing the tempo limit, and persons tend to walk and ride a bike more often. The modal split for both runs is given in Figure 2; please note that "iv" denotes motorized individual traffic.

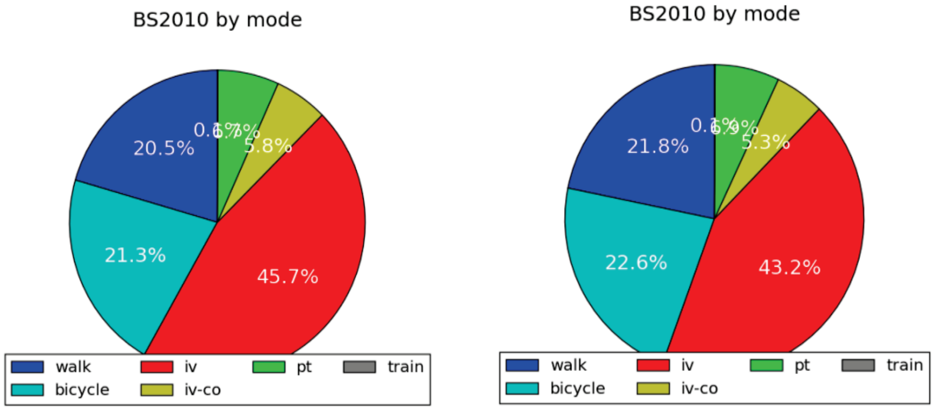

Figure 2: Modal split obtained from the simulation of Brunswick before (left) and after (right) introducing the tempo limit.

Figure 3 shows the effects on the road network, including the traffic volumes and the NO_x emissions. Because the amount of individual motorized traffic gets lower after introducing the tempo limit, almost no roads are heavier occupied than before implementing it. Consequently, an overall decrease in NO_x emissions can be found. Please note that both figure (1 and 3) use different initial demands and use different scales. Thereby, only qualitative changes can be obtained when comparing them.

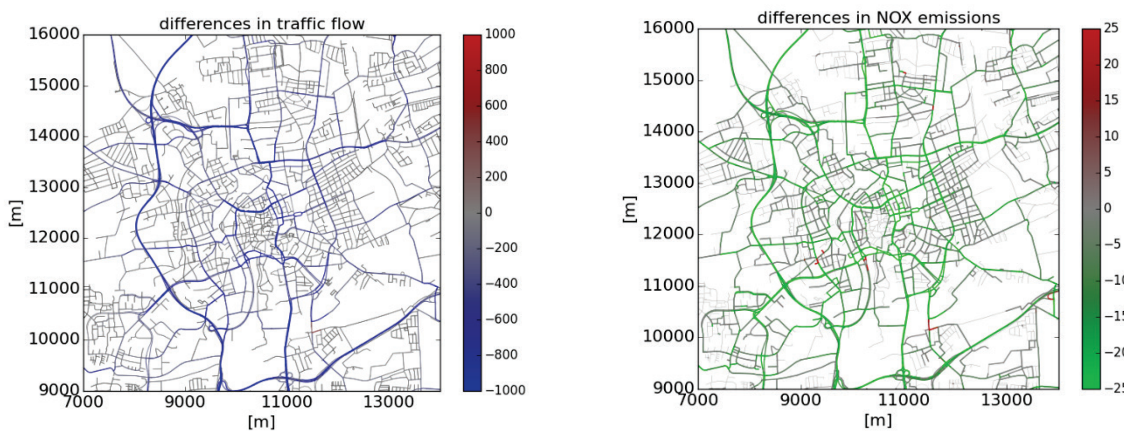

Figure 3: Changes in traffic flow in vehicles/day (left) and NO_x emissions in g/km/h (right) after introducing a tempo limit when taking changes in mode choice into account.

6. COUPLING

Obviously, both simulator types should be coupled for properly computing the effects of developments and measures on the overall traffic state. The example that considers changes in flow and demand shown before was set up manually – the travel time matrices have been set and the demand was recomputed. But in most cases, one should assume that the computation of changes should be performed using iterative subsequent execution of both simulators. Starting from the base case, a measure's effects on traffic are computed, first. Then, in each iteration step, the effects of the transport network's performance are computed and given back to the demand computation. This should be performed until the changes in traffic behavior fall under a given threshold.

Such a combination of a microscopic traffic flow simulation and an agent-based demand model has been developed in the context of the project “Verkehr und Umwelt” (“traffic and environment”) at the German Aerospace Center, respectively using “SUMO” and “TAPAS”. This coupling's workflow is presented in Figure 4 and will be outlined in the following.

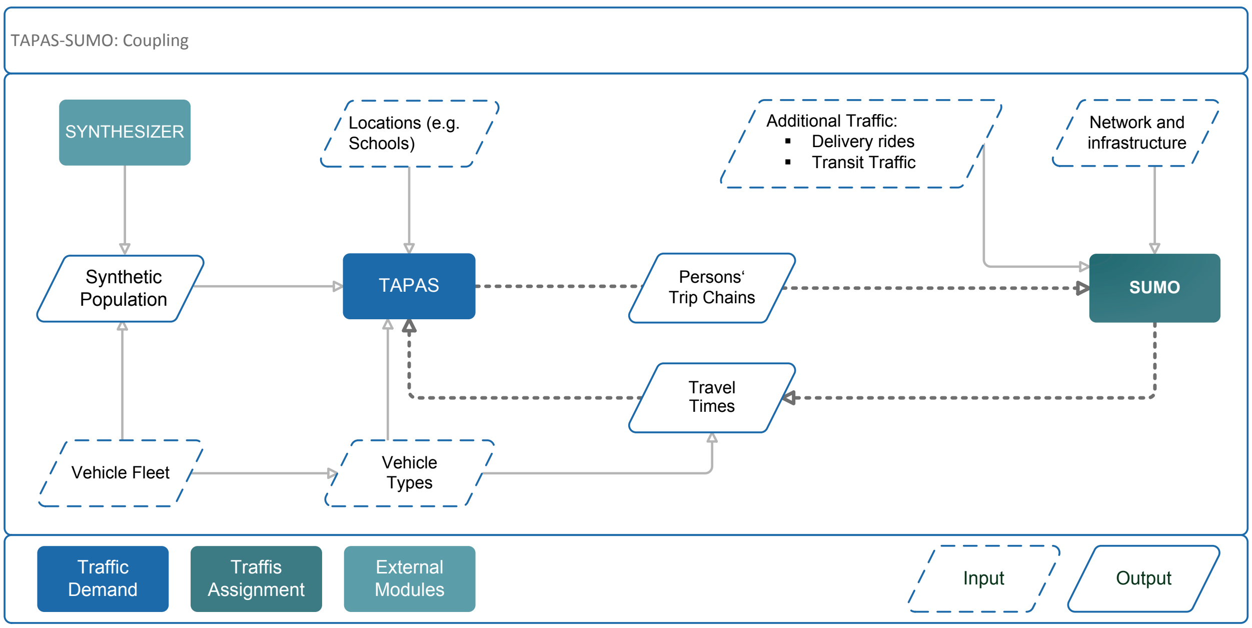

Figure 1: Data flow between the coupled simulations TAPAS and SUMO

Based on the initial inputs, TAPAS computes a demand for the described region, first. The demand consists of single trips over the day for every individual the region's population consists of. Every trip contains the information about its source and destination position, encoded via addresses. Additionally, the type of the used vehicle, the departure time and the expected travel time are given. Currently, only trips performed by private cars are regarded. In the next step, this trip list is given to SUMO, which performs an assignment of the vehicles to the road network. The assignment process assigns a route to every vehicle, taking into account the changes in travel times under different network loads for obtaining a user equilibrium. Additionally given traffic volumes can be included “on top”, e.g. for delivery or transit traffic not covered by TAPAS. The result of the process are new travel times for the road network which are aggregated to travel time matrices between the region's traffic assignment zones. These travel time matrices are used as input for TAPAS within the next iteration step.

The so obtained system iteratively computes changes of the traffic system's behavior, regarding both, changes in mode choice, and traffic flow.

7. SUMMARY

This report described the benefits of microscopic models for traffic demand and traffic flow, outlines their tasks, their inputs, the models used within them and the applications that may be performed using them. It shows that the major shortcomings in replicating the effects of social, regulatory, technical, or operational changes can be solved by a joined usage of both simulation classes. Only if a feedback is given, effects on the overall traffic system can be determined. The report also outlined an implemented simulation system that realizes this feedback by coupling the traffic demand model “TAPAS” and the traffic flow simulation “SUMO”.

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